PROJECT TECHNICAL REPORT
TASK ASPO 5A

PLUME-SURFACE INTERACTION ANALYSIS

NAS 9-4810

22 July 1966

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

TRW SYSTEMS

TRW INC.

National Aeronautics & Space Administration
Manned Spacecraft Center
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Attention: Mr. R. V. Battey (PM3)
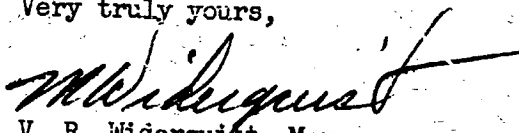Mission Operations Division
Apollo Spacecraft Program Office

Subject: Project Technical Report No. 05952-6001-R000
"Plume-Surface Interaction Analysis"

Gentlemen:

A special assignment under Task ASPO-5A initiated work described in the Task Assignment, "LEM Descent Engine Plume-Surface Flow Interaction Characteristics" pending final release to TRW (ref. TRW 6510.4-90 dtd 23 May 66). This Task Assignment was withdrawn on 30 Jun 66 with the requirement that the work accomplished be reported under Task ASPO-5A. The subject report satisfies this requirement and covers the initial analytical work on plume-surface flow interaction.

In this analysis, the approximate normal shock location produced by the interaction of the vacuum exhaust plume of a rocket nozzle and the lunar (flat) surface was determined. The results of this study are suitable for preliminary analysis of the plume-surface interaction upon the LEM vehicle as it approaches the lunar surface, and for lunar soil erosion estimates. This analysis (Phase I of the proposed task) is considered adequate for preliminary analyses of lunar landing phenomenon, but results are increasingly in error for increasing transverse distances from the system center line, and at small value of h/r_e, the normalized engine standoff height.

Very truly yours,

V. R. Widerquist, Manager
Task ASPO-5A

Apollo Spacecraft Systems Analysis Program

/cm

Enclosure

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TRW SYSTEMS

INTRODUCTION

The approximate shock location produced by the interaction of the vacuum exhaust plume of a rocket nozzle and the lunar (flat) surface was determined. The surface was taken to be placed normal to the centerline of the nozzle. The analysis presented by Roberts[1] was employed to locate the shock. The rocket exhaust plumes were computed by the method of characteristics[2] for a gas with a constant ratio of specific heats (γ). The resulting centerline density and transverse density distributions from the plume program were compared with those presented by Roberts and were found to agree for distances greater than 3.0 nozzle exit radii. Newtonian pressure distributions on the surface were computed from information generated by the plume program as a function of the height of the nozzle above the surface for four different combinations of nozzle geometry (cone and contour) and γ (1.24 and 1.28).

The results of this study are suitable for preliminary analysis of the effect of the plume-surface interaction phenomenon upon the LEM vehicle as it approaches the lunar surface and the lunar soil erosion which occurs during landing.

This report summarizes the analyses performed to approximately locate the shock layer resulting from the nozzle-plume/lunar-surface interaction. This effort was to form the first phase of a program to analyze lunar landing plume-surface interaction phenomenon. Subsequent phases of the study were to employ the Method of Integral Relations to accurately analyze the shock layer flows to determine the actual flow field properties, e.g., density, pressure, velocity, etc., within the shock layer and the ground shock location for both flat and curved surfaces. The results of this complete study would have allowed the accurate determination of the lunar ground shock location and surface flow conditions during normal lunar landing for use in LEM landing dynamics studies and lunar surface erosion studies. The effort has been terminated at NASA's request at the completion of the Phase I effort summarized in this report.

DISCUSSION

As the LEM vehicle approaches the lunar surface with the Descent Engine (LEMDE) operating, a shock layer will be formed due to the

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interaction between the rocket engine exhaust plume and the lunar surface. At some point during the descent phase, the LEM vehicle landing legs and engine may intersect this shock layer, causing unsymmetrical loads to be imposed upon the vehicle. In addition, the lunar surface may erode during landing, resulting in a dangerous landing situation. Fundamental to all lunar landing studies is the accurate determination of the plume surface flow field.

The present analysis was performed to provide preliminary information regarding the location of the shock layer with respect to the descending LEM using the analysis presented by Roberts[1]. Inherent to Roberts' analysis is the assumption that the flow field variables, density, pressure, etc., vary in the issuing rocket plume as if the nozzle were a point source. Thus, Roberts' analysis is not valid when the exit of the nozzle is "close" to the lunar surface and at "large" distances from the centerline of the system.

A comparison was first undertaken to determine how well the assumed density distribution-axial and transverse-predicted by Roberts matches a corresponding method of characteristic solution of the plume[2]. The resulting comparison is depicted in Figures 1 and 2. Figure 1 is a plot of the centerline density distributions computed by both methods as a function of the distance of the nozzle above the surface. Figure 2 shows the transverse density distributions for a value of $h/r_e = 100$. An examination of both figures indicates that Roberts' centerline density distribution agrees with the characteristics solution beyond an h/r_e value of 3. The transverse distributions show reasonable agreement at $h/r_e = 100$.

Based upon these considerations, the shock locations from Roberts were computed for the following four combinations of nozzle geometry and (constant) ratio of specific heats, γ.

TABLE I

Nozzle Geometry and Ratio of Specific Heats

Nozzle Type	γ
Cone	1.24
Cone	1.28
Contour	1.24
Contour	1.28

The lip conditions of Mach number and flow angle of the contoured nozzles were determined by a computer program[3] which found the optimum contour which maximized the two-dimensional thrust coefficient for an expansion area ratio equal to the LEMDE ($\varepsilon = 47.36$).   Two values of γ were employed due to the uncertainty in the appropriate choice of γ suitable for the LEMDE plume.   The corresponding exit conditions for the conical nozzles were found by computing the cone expansion half-angle (21.64°) that fits the present LEMDE envelope.   Constant Mach number maps for the four cases were processed by the plume program and are reproduced as Figures 3 through 6.

The four shock shapes were computed following the outlined procedure,[1] and are shown in Figure 7.   As mentioned above, Roberts' analysis is valid only for distances of the nozzle exit above the surface greater than some critical dimension.   Based on the LEMDE exit radius of 2.383 ft, the region of validity is tabulated below:

TABLE II

Limit of Applicability of Roberts' Analysis

Nozzle	γ	$h_{crit.}$, ft
Cone	1.24	4.87
Cone	1.28	5.50
Contour	1.24	4.52
Contour	1.28	5.05

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As can be seen from the above table, the limit of applicability of the analysis is not very far from the surface, i.e., the analysis applies whenever the nozzle exit is greater than 5-6 ft above the lunar surface. An examination of Figure 7 shows that the shock shape is concave upward near the axis, $r/h \approx 0$, and becomes concave downward at greater transverse distances from the axis of the flow field. A point of inflection exists because most of the mass flux issuing from the exhaust nozzle is concentrated around the nozzle centerline. Thus, to satisfy mass continuity, i.e., the balancing of the mass flux entering the shock layer with the corresponding flux within the shock layer, the shock layer must possess this typical "S" shape. The effects of lip conditions, flow angle and Mach number, as well as specific heat ratio, may also be determined from Figure 7.

The Newtonian pressure distribution along a flat surface was determined by employing the characteristic plume results. This procedure assumed that the shock was parallel to, and coincident with, the surface, i.e., the shock layer was of infinitesimal thickness. Thus, the surface pressure distribution could be found by considering that the normal component of momentum in the plume was converted into pressure using the following relationship:

$$P_T = P + \rho V^2 \cos^2 \theta \tag{1}$$

This procedure was employed for values of the height of the nozzle above the surface, h, of $h/r_e = 1, 2, 5, 10, 20, 50$ and 100 for the four combinations of contour-γ listed in Table I, and the results are shown in Figures 8-11. Since the actual resulting shock layer is non-zero in thickness and increases away from the stagnation point, the calculated Newtonian surface pressure distribution becomes less accurate away from the axis. If it is further assumed that the flow is essentially adiabatic, that is, no energy transfer from the gas to the surface, then it is evident that the gas temperature at the stagnation point rises to the combustion chamber value for a perfect gas and all flow properties along the surface streamline, h = 0, can be determined from standard compressible flow relationships[4]. Thus, first estimates can be obtained from the present analysis for a boundary layer type of analysis of surface erosion phenomenon.

Although the present results are adequate for preliminary analyses of lunar landing phenomena, the results are increasingly in error for increasing transverse distances from the system centerline and at small values of h/r_e, the normalized engine standoff height. In order to determine accurate shock layer locations and surface flows at small standoff heights and away from the axis, an analysis such as was to be performed in later phases of this study must be performed.
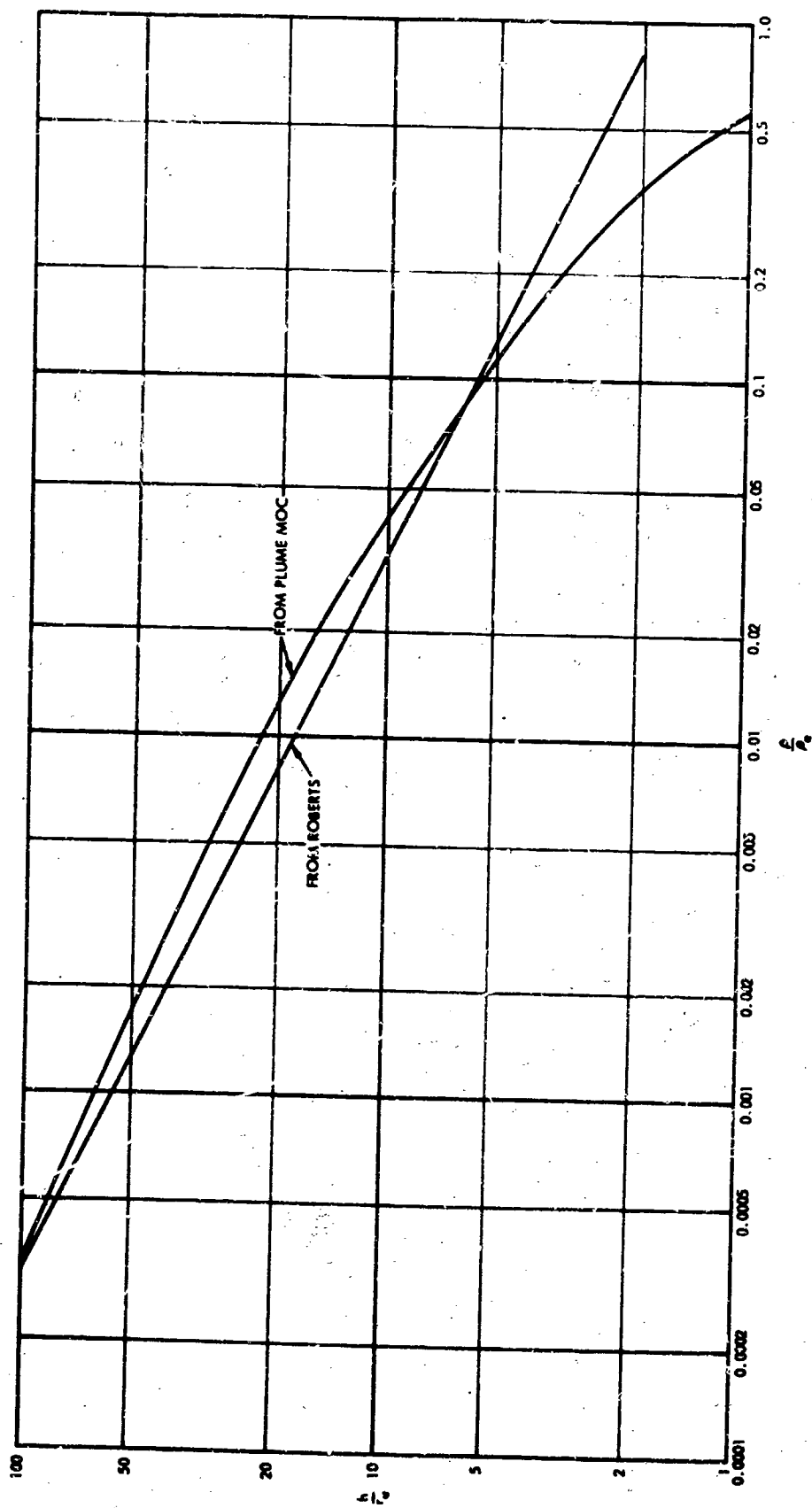
Figure 1. Centerline Density Distribution Comparison, Cone, $\gamma = 1.24$

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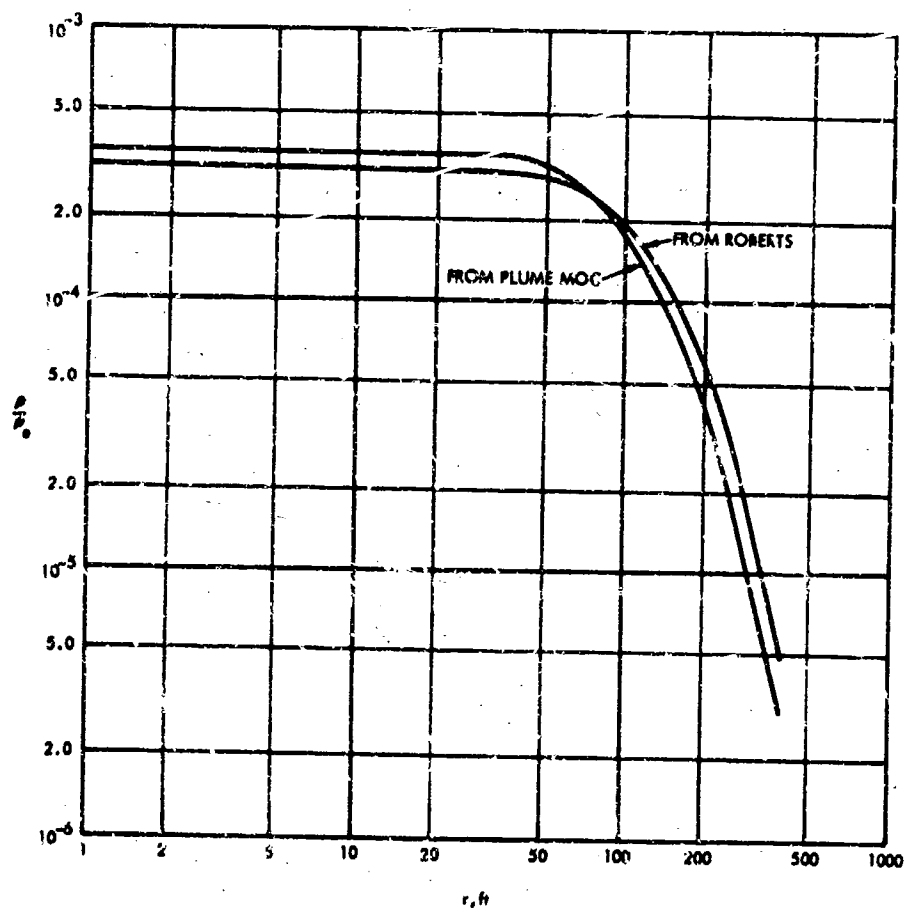
Figure 2. Transverse Density Distribution Comparison, $h/r_e = 100$ (Cone, $\gamma = 1.24$)
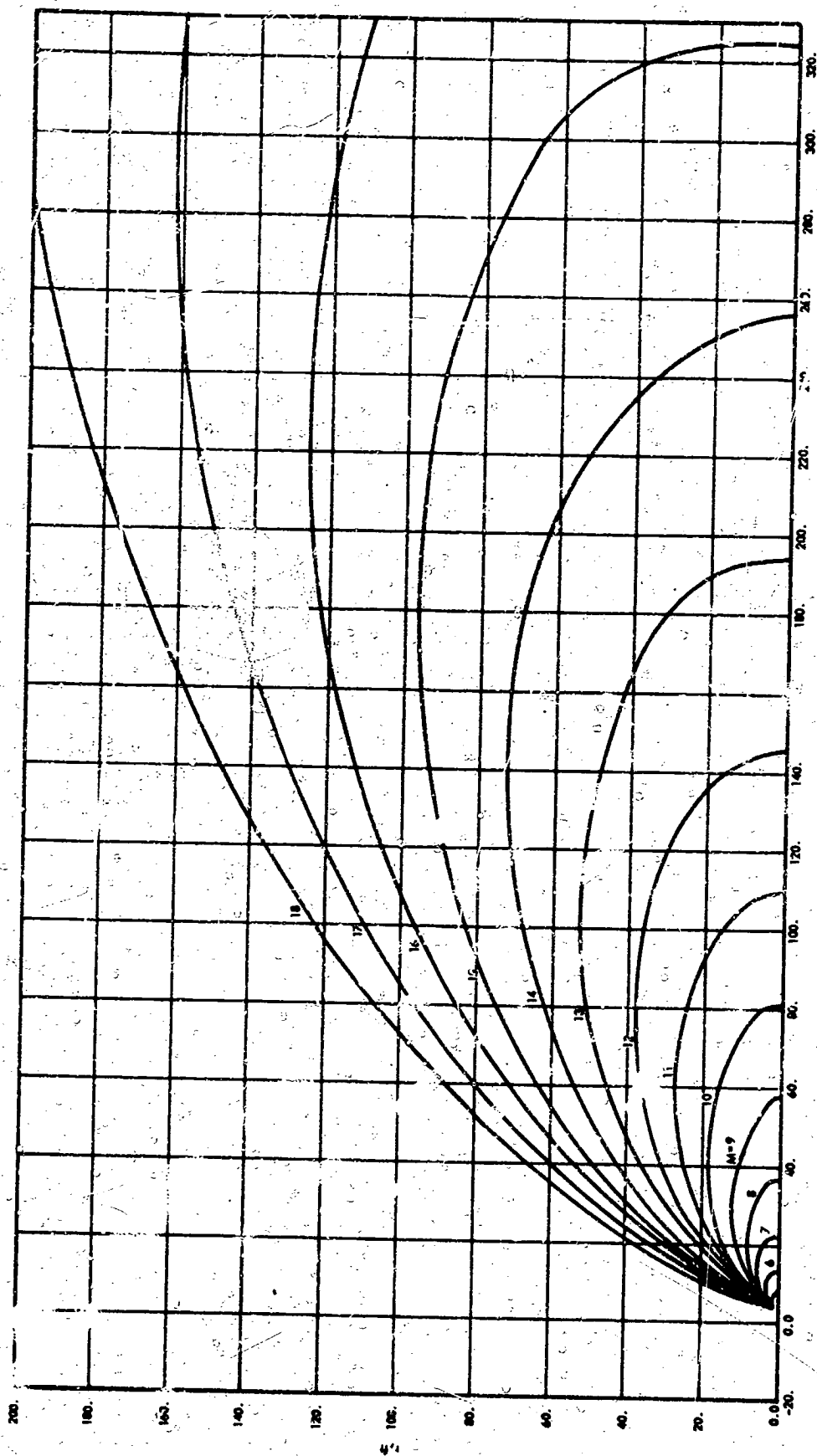
Figure 3. Constant Number Map, Cone, $\gamma = 1.24$
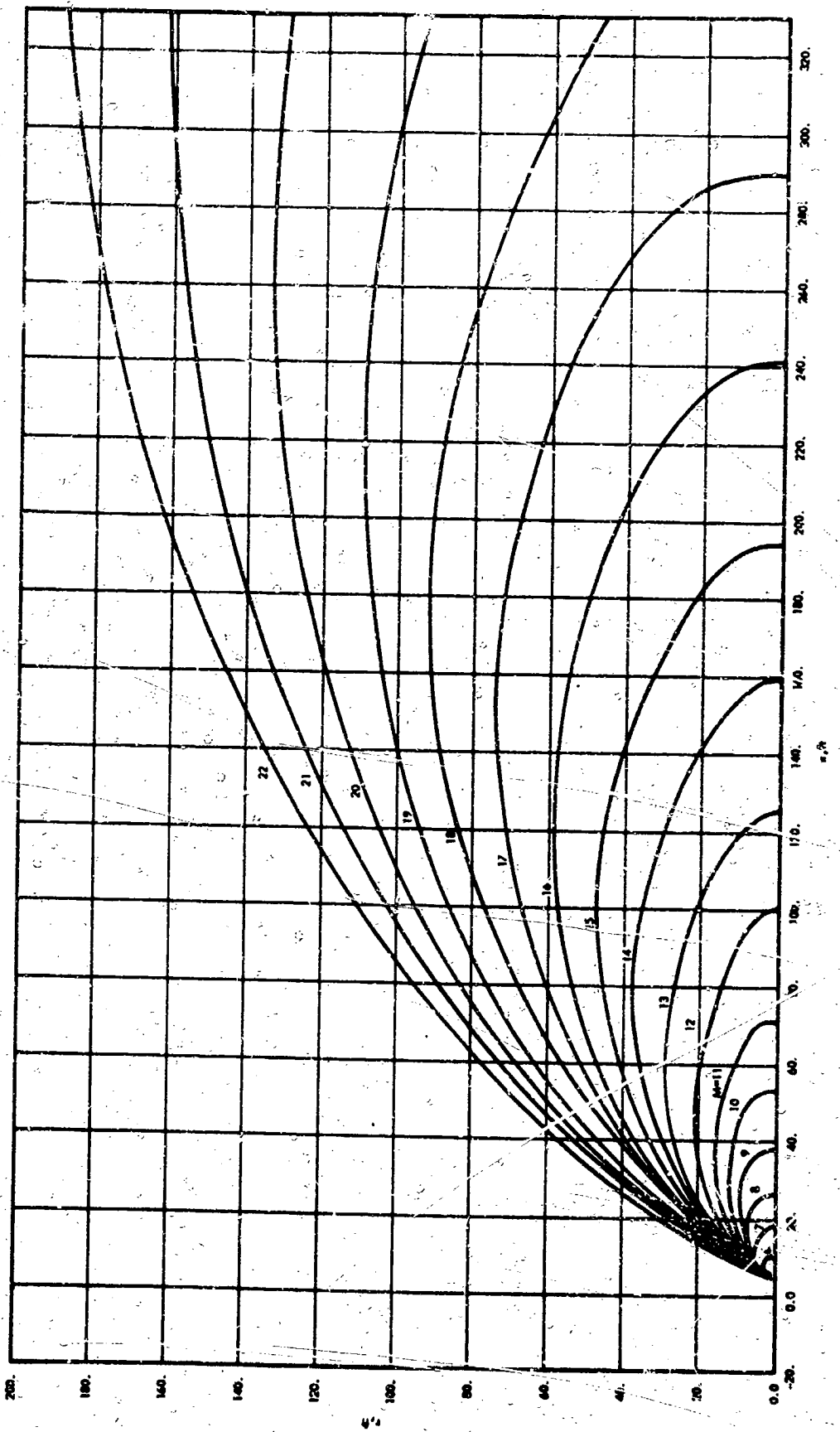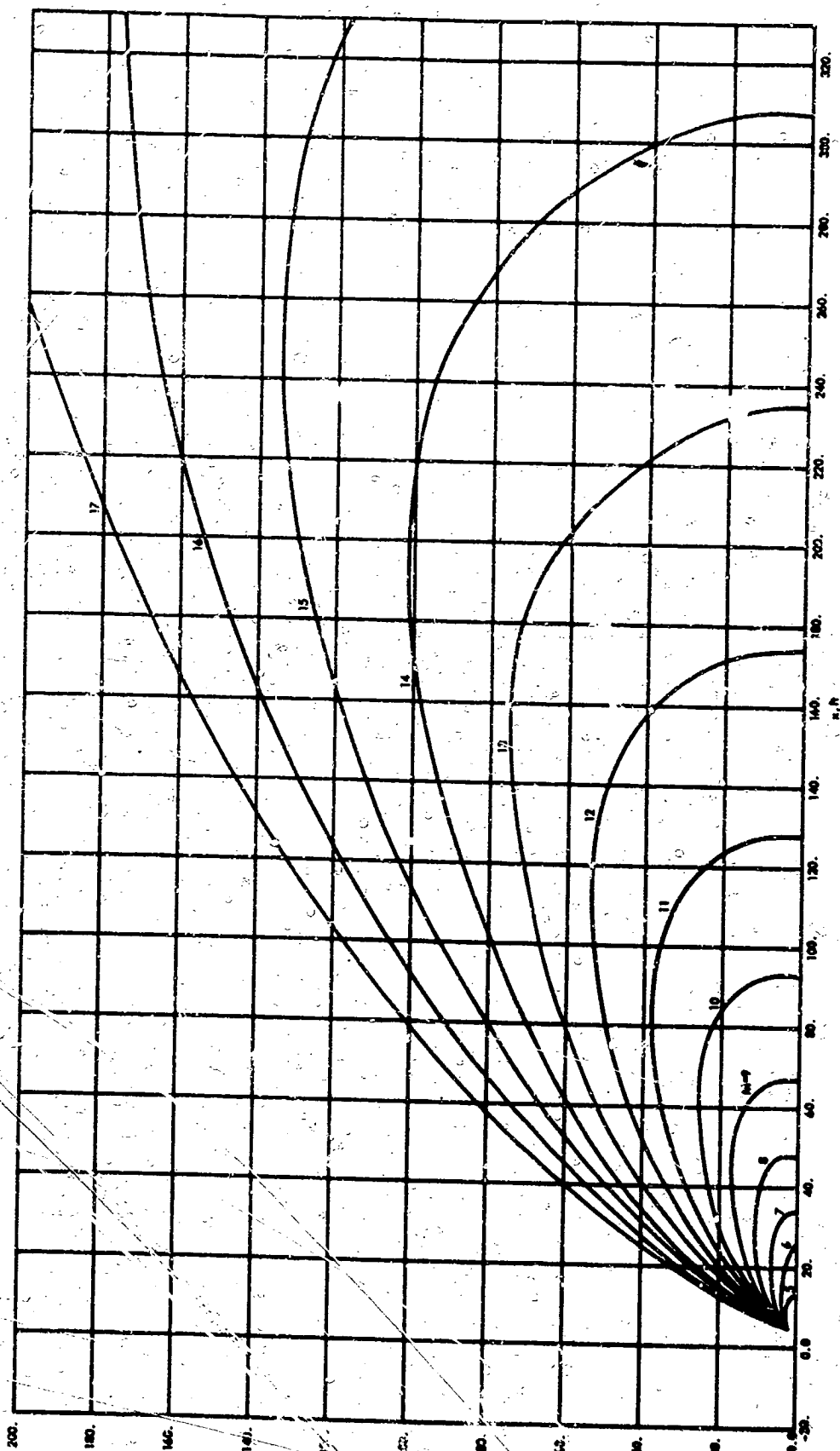
Figure 4. Constant Mach Number Map, Cone, $\gamma = 1.28$

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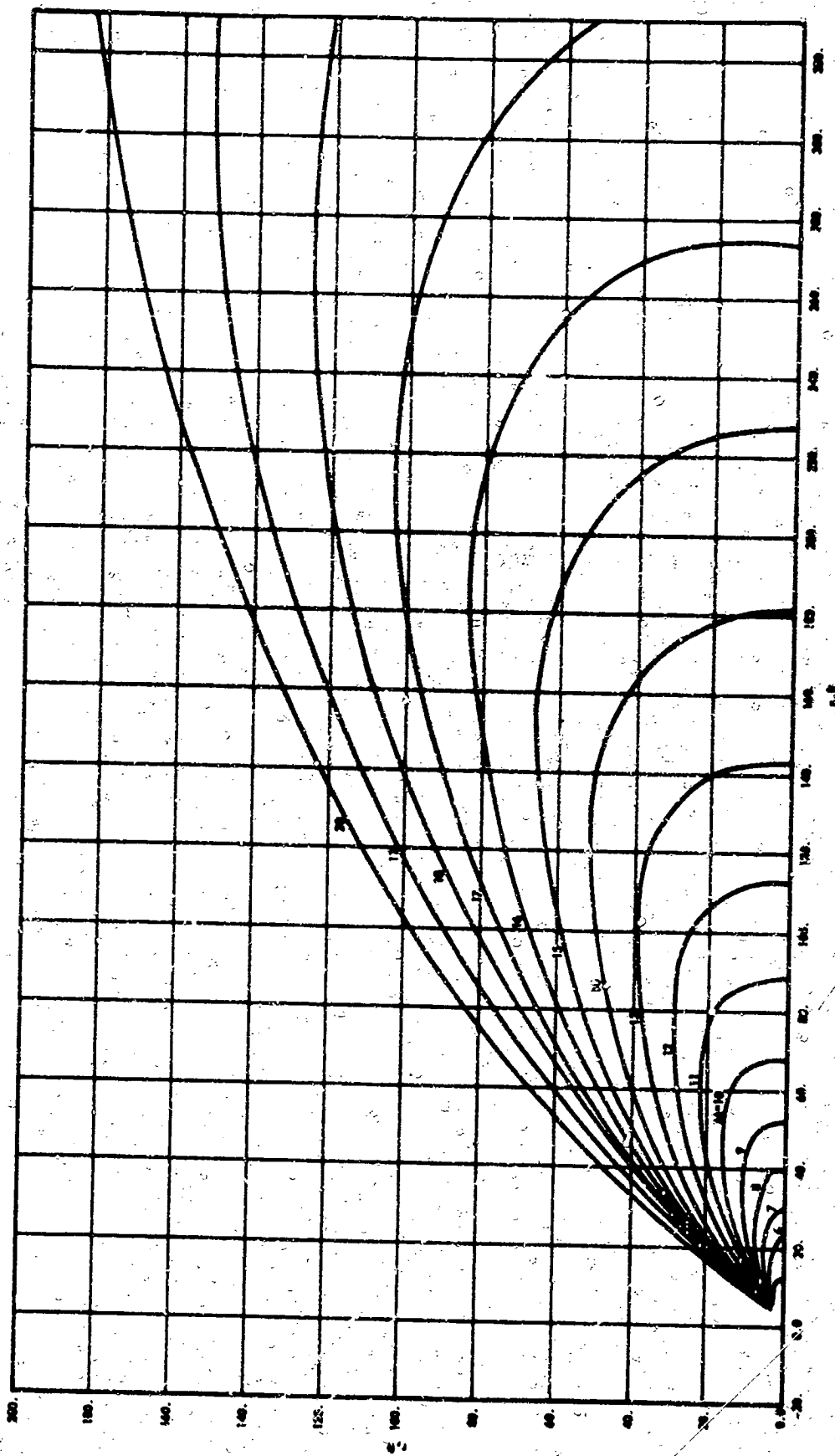Figure 5. Constant Mach Number Map, Contour, $\gamma = 1.24$

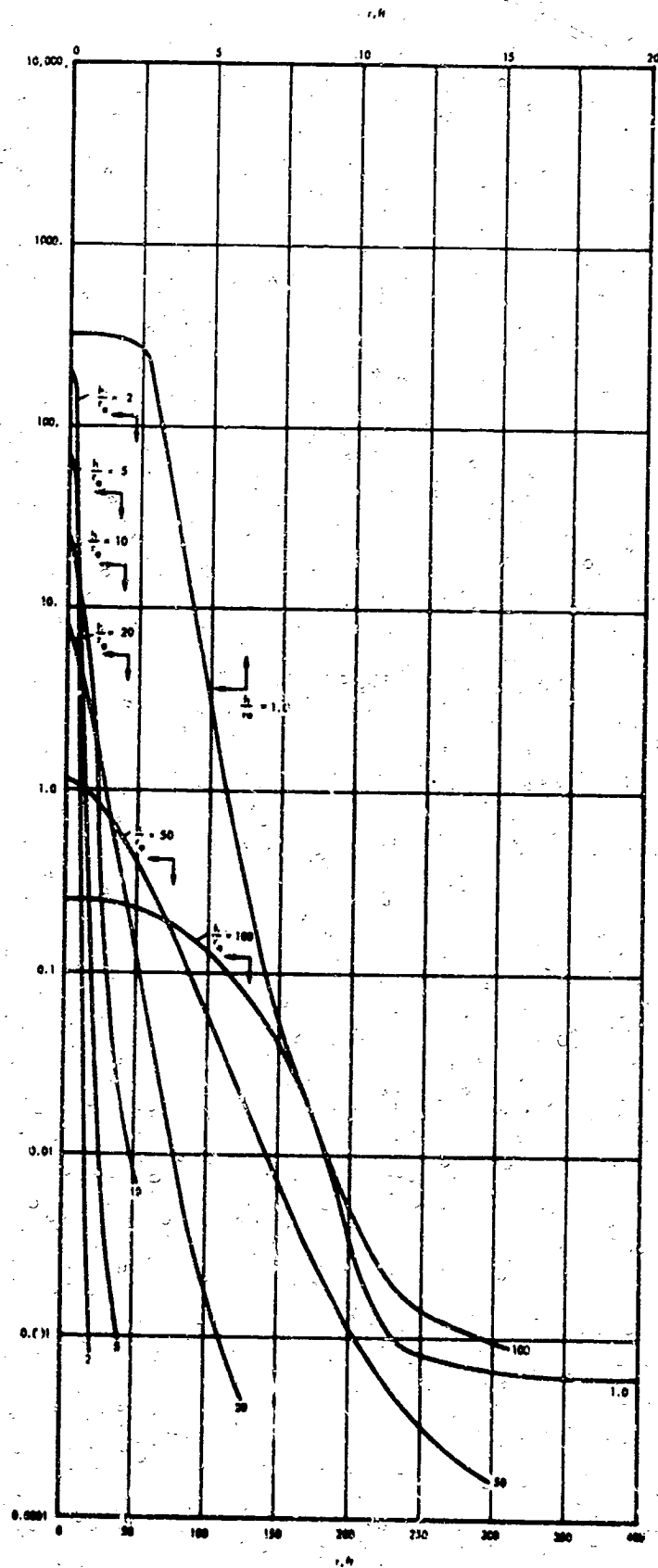Figure 6. Constant Mach Number Map, Contour, $\gamma = 1.28$

Figure 7. Approximate Shock Shapes

Figure 8.   Newtonian Surface Pressure
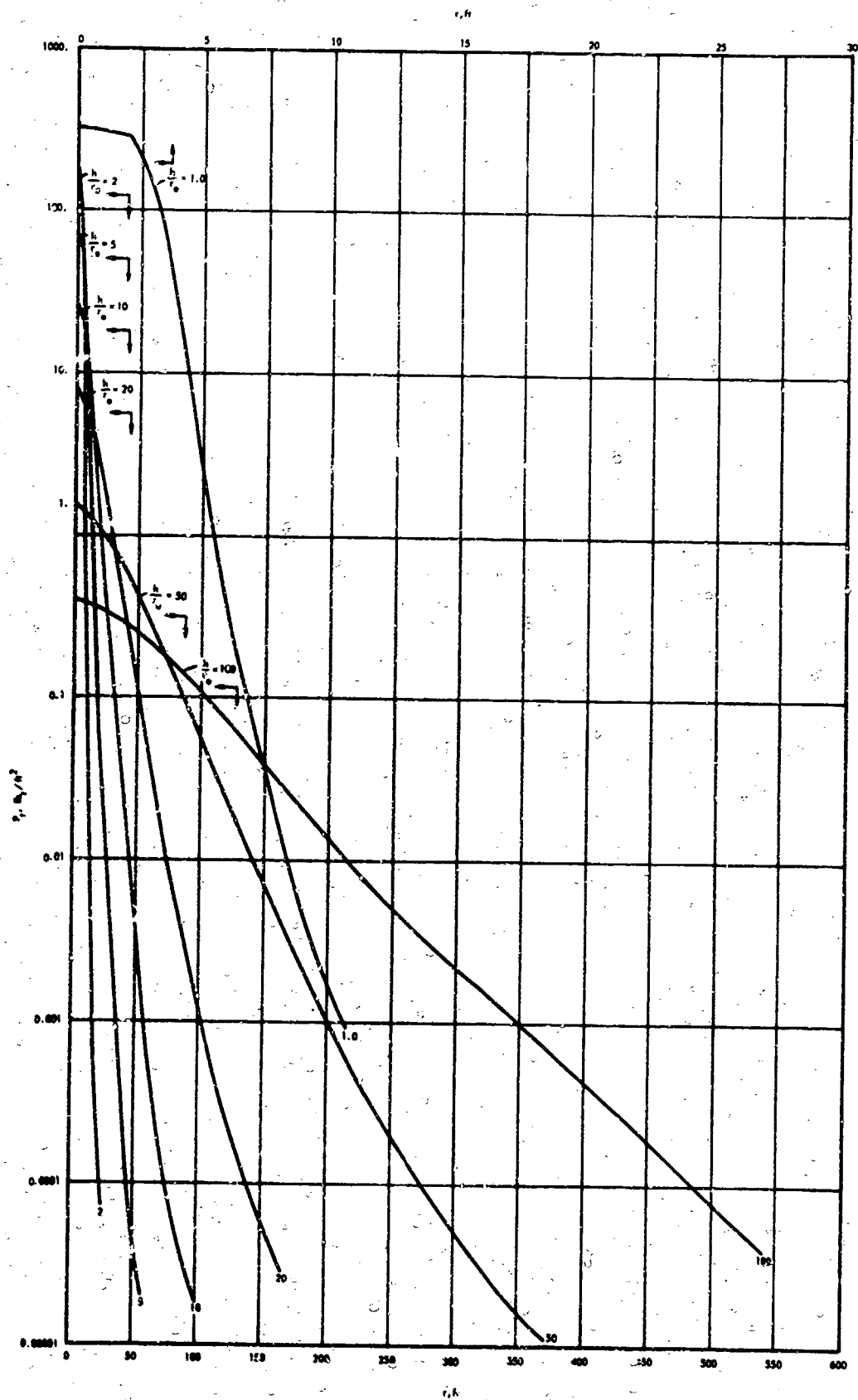Distributions, Cone, $\gamma = 1.24$

Figure 9. Newtonian Surface Pressure
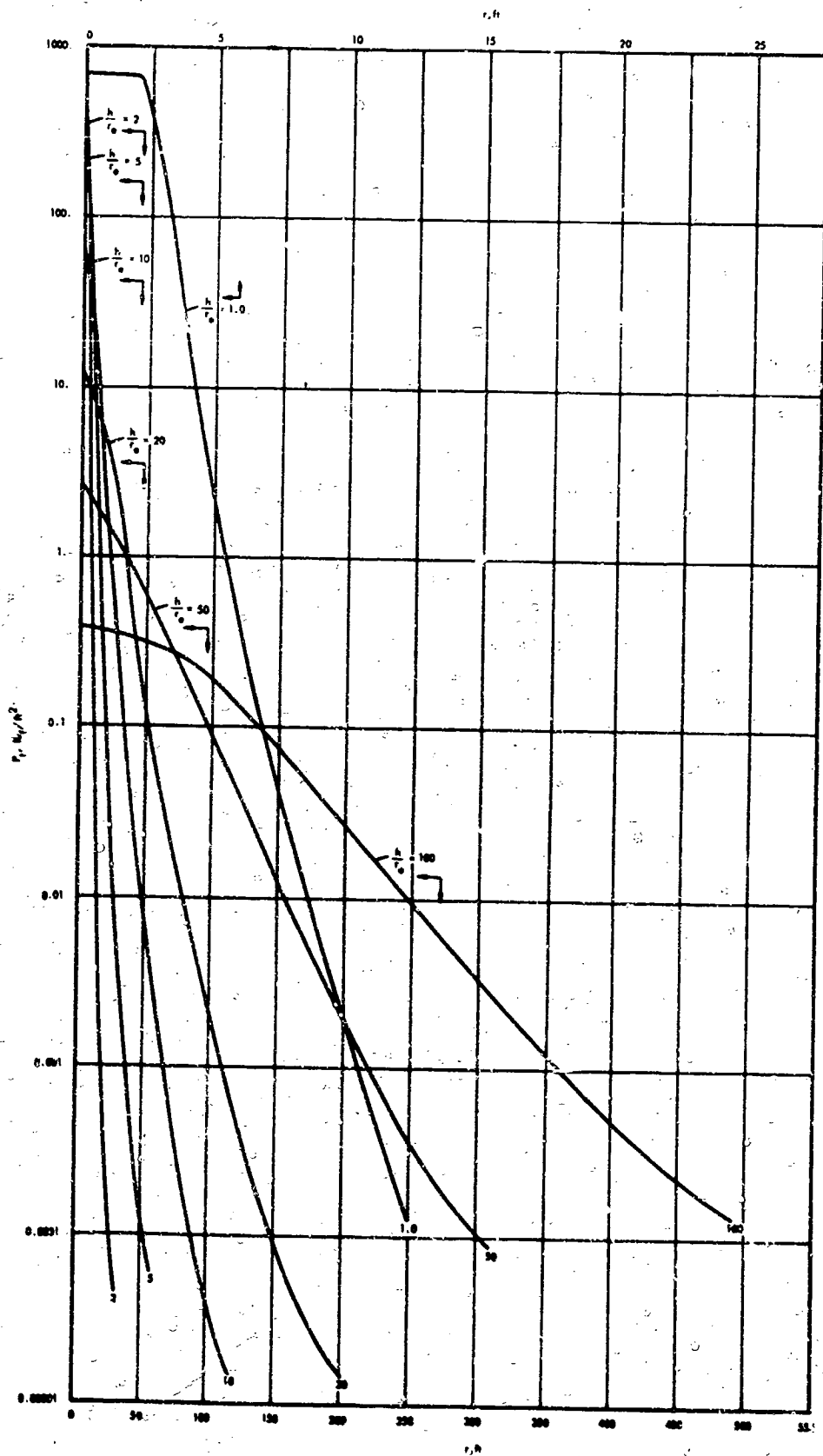Distributions, Cone, $\gamma \approx 1.28$

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Figure 10. Newtonian Surface Pressure
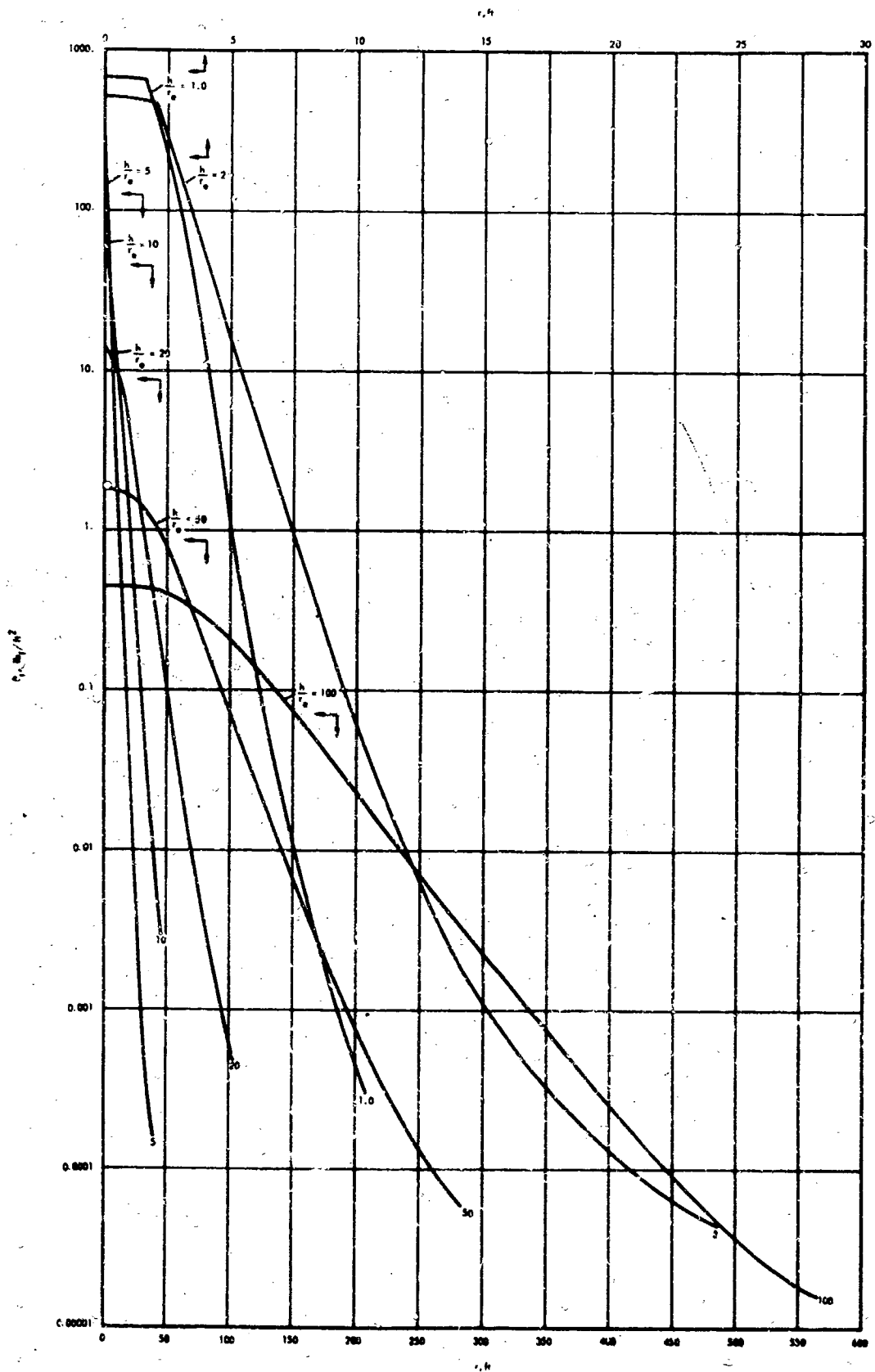Distributions, Contour, $\gamma = 1.24$

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Figure 11.   Newtonian Surface Pressure
Distributions, Contour, $\gamma = 1.28$

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1. Roberts, L., "The Action of a Hypersonic Jet on a Dust Layer," Institute of Aerospace Sciences Paper No. 63-50, January 1963.

2. Prozan, R. J., "PMS Jet Wake Study Program," Lockheed Missiles and Space Division Report No. LMSC 919901, 9 October 1961.

3. Nickerson, G. R. and Kempf, D. M., "The Rao Method Optimum Nozzle Contour Program," TRW/STL Report No. 9852.21-29, 1 October 1964.

4. Shapiro, A. H., The Dynamics and Thermodynamics of Compressible Fluid Flow, Vol. I, Ronald Press Company, 1953.

NOMENCLATURE

h	distance of the nozzle above the lunar surface, ft
p	gas static pressure, lb_f/ft^2
P_T	Newtonian surface pressure, lb_f/ft^2
r	transverse distance from the nozzle centerline, ft
r_e	exit radius of the nozzle (= 2.383 ft for the LEMDE), ft
V	Gas velocity, ft/sec
γ	ratio of specific heats, (= C_p/C_v)
θ	gas streamline angle with respect to nozzle centerline, degrees
ρ	gas density, lbm/ft^3